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Non-nuclear, low-carbon, or both? The case of Taiwan

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Abstract

The Fukushima nuclear accident in Japan has renewed debates on the safety of nuclear power, possibly hurting the role of nuclear power in efforts to limit CO₂ emissions. I develop a dynamic economy-wide model of Taiwan with a detailed set of technology options in the power sector to examine the implications of adopting different carbon and nuclear power policies on CO₂ emissions and the economy. Absent a carbon mitigation target, limiting nuclear power has a small economic cost for Taiwan, but CO₂ emissions may increase by around 4.5% by 2050 when nuclear is replaced by fossil-based generation. With a low-carbon target of a 50% reduction from year 2000 levels by 2050, the costs of cutting CO₂ emissions are greatly reduced if both carbon sequestration and nuclear expansion were viable. This study finds that converting Taiwan's industrial structure into a less energy-intensive one is crucial to carry out the non-nuclear and low-carbon environment.

Key Words: Economy-wide Analysis; Non-nuclear Policy; CO₂ Reduction

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1. INTRODUCTION

Concern about global warming seems to make nuclear power an attractive option. The Fukushima nuclear accident in Japan, however, has renewed the debate on the safety of nuclear power, possibly hurting the role of nuclear power in efforts to limit CO₂ emissions. For instance, Japan has decided to increase its renewable energy supply and abandon the expansion of nuclear industry, and Germany will shut all nuclear reactors by 2022 (Fackler, 2011; McGroarty and Fuhrmans, 2011).

In Taiwan, the ongoing nuclear power project is intensely debated as well. Because of safety concerns and challenges in finding repository sites for nuclear waste, many people are urging the government to stop building the Longmen Nuclear Power Station. The concern persists, even after the government announced that Longmen will be Taiwan's fourth and last nuclear power project. On the other hand, others argue that the nuclear option should be kept since it is a viable approach to curb CO₂ emissions effectively without reducing electricity supply. This is especially important for Taiwan since, because of resource constraints, the role of renewable power sources may remain insignificant.

While more and more countries try to cut CO₂ emissions to reduce the threat of global warming, we still have limited understanding about the potential effects of pursuing low-carbon growth with or without the nuclear option. Thus, an economy-wide analysis that studies the role of nuclear power in pursuing a low-carbon economy is crucial, especially for a small economy such as Taiwan, which lacks natural resources and must import most of its energy supply.

Until now, existing studies have found that nuclear power is an effective tool to curb CO₂ emissions from the power sector, especially in the long run (Wang *et al.*, 2011; Yang, 2011; Bensmann, 2010; Yun and Baker, 2009; Mori, 2000). They do not, however, analyze cases where nuclear power is no longer an option. One exception is Mori (2000), which found that limiting CO₂ emissions without nuclear power expansion requires a higher level of carbon sequestration implementation and would incur a greater negative impact on global GDP. Nevertheless, higher resolutions on regions and sectors are not presented in the research. A number of studies, on the other hand, examined energy and nuclear policies in Taiwan separately (Lin, 1997; Hsu *et al.*, 1998; Huang, 2000; Liang and Kuo, 2003; Huang, 2007; Lin and Su, 2008; Liang, 2008; Yang, 2009; and Ko *et al.*, 2010). None of the research, however, has presented a framework that can simultaneously assess the potential effects of pursuing a non-nuclear and low-carbon growth scenario. While other studies have explored CO₂ reduction impacts on different sectors or technologies (Bureau, 2011; Chen *et al.*, 2011; Karplus *et al.*, 2009; McFarland, 2009), the interaction between non-nuclear option and low-carbon policy is beyond their research scopes.

To fill this gap, this study takes Taiwan as an example and explores the policy implications of pursuing low-carbon growth with or without the nuclear option. With the low-carbon policy, Taiwan will eventually cut its CO₂ emissions to 50% of 2000 levels by 2050. Under the non-nuclear policy, while the existing three nuclear power plants of Taiwan will continue to operate until the end of their lives in 2020s, the coming nuclear power plant under construction will

never be allowed to join the grid. In addition, under the low-carbon policy, a counterfactual scenario that allows further expansion of nuclear power beyond the government's plan will also be discussed.

This study will answer the following questions: (1) what will be the economic implications of carrying out the low-carbon policy with or without the nuclear option; and (2) what will be the roles of various generation technologies under different policy scenarios? To conduct the analysis, a multi-sector recursive dynamic general equilibrium model is built. The model takes into account the optimized behaviors of distinct producers and a representative household, and their interactions through various market transactions. This study also disaggregates the electricity sector into six sub-sectors to account for the diversified carbon footprints of various generation technologies, and to represent the cost of CO₂ reduction, it considers a hypothetical carbon tax that covers all combustion CO₂ emissions, which constitute about 96% and 88% of Taiwan's national CO₂ emissions and GHG emissions as of 2008, respectively (EPA, 2009).¹ Further, this study presents a new approach that improves the modeling for the relationship between dispatchable generation (gas and hydro power for instance) and non-dispatchable generation (wind power in particular).

The rest of this study is organized as follows: Section 2 provides the energy and policy background of Taiwan; Section 3 describes model settings and the strategy of modeling dispatchable and non-dispatchable electricity generation; Section 4 presents the economic, demographic, technological, and emissions data used in this study; Section 5 explores the economy-wide effects of various policies; and Section 6 provides conclusions, which summarize contributions of this study and discuss future research directions.

2. ENERGY AND POLICY BACKGROUND OF TAIWAN

Taiwan currently imports 99% of its energy supply. As **Figure 1** shows, in recent years over 90% of the supply comes from fossil fuels (Bureau of Energy, 2011a). Figure 1 also reveals that in 2010, industrial sectors accounted for almost half of the energy demand (44.5%), following by exports of refined oil products (12.1%), transportation use (10.7%), service sectors (9.1%), household (8.9%), etc. (Bureau of Energy, 2011b). For decades, while the development of petroleum, chemical, iron, cement and non-metallic industries have played crucial roles in Taiwan's economy, they are relatively energy-intensive compared to other sectors.

For Taiwan, since the domestic energy consumption highly relies on fossil fuels, to diversify that consumption, the government has tried to promote the use of various types of energy, including nuclear power and renewables. **Table 1** shows that, as of 2008, coal-fired, gas-fired, oil-fired, nuclear, and hydro-powered generation accounted for roughly 52.5%, 19.4%, 6.0%, 17.1%, and 3.3% of Taiwan's national electricity supply, respectively. Currently, the government is expanding the country's nuclear power capacity by building the Longmen Nuclear Power

¹ The hypothetical carbon tax requires individuals to internalize the cost of emissions imposed on others and on future generation (Metcalf and Weisbach, 2009). In particular, the larger tax base ensures a less distortionary impact on resource allocation and thus avoids overestimating the economic burden of cutting emissions.

Station, now in the last construction phase (Bureau of Energy, 2011c; The Nuclear Association of Taiwan, 2011). With a capacity of 2750 MWe, the plant would need only 80 tons of uranium feedstock in a year to generate the same amount of electricity as 515 million tons of coal or 143 million tons of natural gas (The New Taipei City Government, 2011).²

The government also set a target of reducing national CO₂ emissions to the 2005 and 2000 levels by 2020, and 2025, respectively, and finally cutting emissions to the half of 2000 levels by 2050 (Environmental Protection Administration, 2012). Nuclear power proponents assert that nuclear power is a feasible way to curb CO₂ emissions in Taiwan, which have more than doubled in the last two decades and have made Taiwan become one of the highest per capita CO₂ emissions countries in Asia, as shown in **Table 2**. Taking the power sector for instance, Taiwan has the world's largest coal-fired power plant, and the three largest coal-fired power plants of Taiwan account for around 30% of its national CO₂ emissions, as shown in **Figure 2** (Carbon Monitoring for Action (CARMA), 2013). Proponents of nuclear power argue that without the nuclear option, achieving the emissions reduction target would be next to impossible.

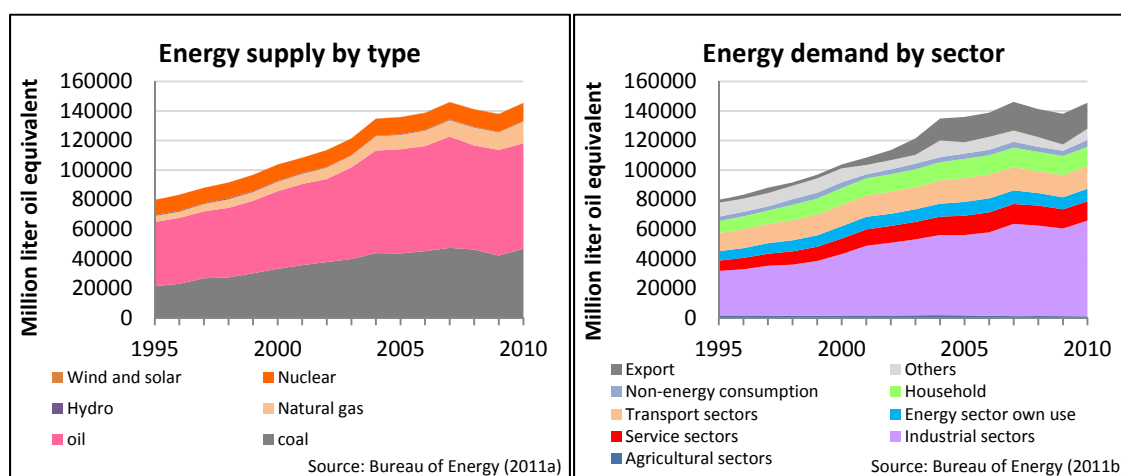


Figure 1. Energy supply and demand in Taiwan.

² As a result, even at the highest historical uranium price level at \$136 per pound in 2007 (Scott, 2011), the fuel cost of a nuclear power plant still constitutes a minor part of its production cost compared to fossil-based power plants.

Table 1. Electricity generation mix for selected countries in 2008.

	World	Taiwan	US	Japan	Germany	France	China	Brazil
Coal	40.8%	52.5%	48.8%	26.6%	45.6%	4.7%	79.1%	2.7%
Gas	21.2%	19.4%	20.8%	26.2%	13.8%	3.8%	0.9%	6.3%
Oil	5.5%	6.0%	1.3%	12.9%	1.5%	1.0%	0.7%	3.8%
Nuclear	13.5%	17.1%	19.2%	23.9%	23.3%	76.4%	2.0%	3.0%
Hydro	16.2%	3.3%	6.5%	7.7%	4.2%	11.9%	16.9%	79.8%
Other	2.8%	1.7%	3.4%	2.8%	11.6%	2.1%	0.5%	4.5%

Source: IEA (2011).

Table 2. CO₂ emissions from energy consumption in 2006 for selected countries.

Country	Per capita emissions (ton-CO ₂ /person)	Total emissions (million ton-CO ₂)
China	4.58	6017.69
India	1.16	1293.17
Japan	9.78	1246.76
Malaysia	6.70	163.53
Philippine	0.81	72.39
South Korea	10.53	514.53
Taiwan	11.40	259.27
Thailand	3.79	245.04
Germany	10.40	857.60
France	6.60	417.75
United Kingdom	9.66	585.71
United States	19.78	5902.75
World	4.48	29195.42

Source: EIA (2009a; 2009b) and Bureau of Energy (2010).

Opponents of nuclear power, on the other hand, emphasize that for Taiwan, the current risk of a devastating earthquake such as the one that occurred in Japan poses serious safety concerns for the existing and forthcoming nuclear power plants, which are all built in areas with high seismic activities close to the coastline, and are considered as few the world's most dangerous nuclear power plants (Rigdon and Keegan, 2011). After the Fukushima accident, while the Japanese government advised residents within 19 miles (30 kilometers) of Fukushima Daiichi plant to evacuate, the U.S. Nuclear Regulatory Commission recommended that Americans within 50 miles (80 kilometers) of Japan's Fukushima Daiichi plant evacuate (Cox et al., 2011). In Taiwan, there are over five million people living within 30 kilometers from the existing nuclear power stations, and more than nine million residents are within 80 kilometers from those plants. Figure 2 shows that, in case of nuclear accident, it would be very difficult for people to evacuate to a safer place in such a populated island. Nuclear opponents argue that the development of less energy-intensive industry, the improvement of efficiency, more utilization of renewable resources, and the advancement of carbon mitigation technology such as carbon capture and storage (CCS) should be the future development path.

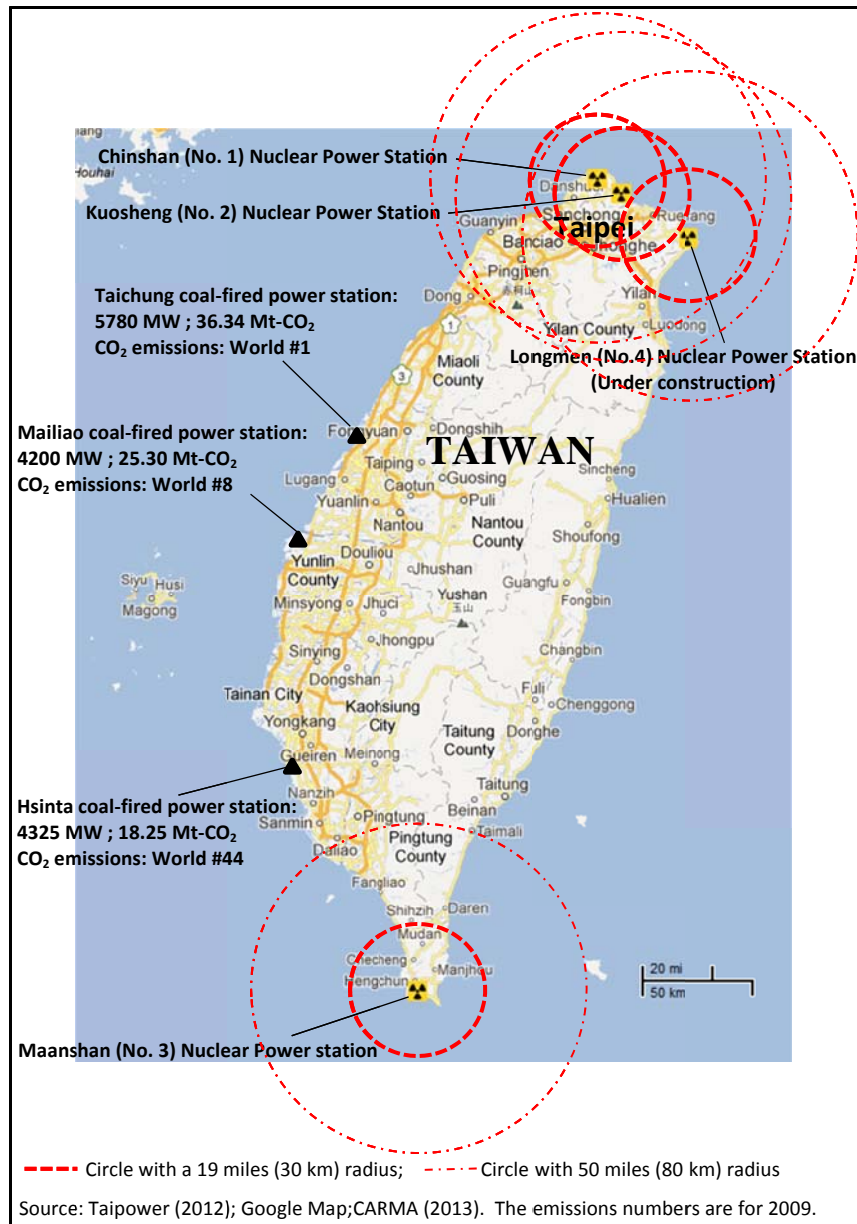


Figure 2. Nuclear power stations and top three coal-fired power stations in Taiwan.

After the Fukushima accident, the Longmen Nuclear Power Station, which was expected to join the grid by the end of 2011, is under scrutiny by experts due to various safety concerns, and its operation has been postponed. However, President Ying-Jeou Ma and his Nationalist Party (KMT) have reaffirmed that the power plant should be operated later. On the other hand, the Democratic Progressive Party (DPP), the main opposition party of Taiwan, has proposed the “non-nuclear homeland policy,” which asserts that the Longmen Nuclear Power Station should

not be operated even after the construction is done, and Taiwan should go non-nuclear after 2025 when all three existing nuclear power plants reach the end of their lives.

In this study, to represent the government's plan, in the business-as-usual (BAU), the Longmen Nuclear Power Station will be allowed to operate from 2015 onward, but there will be no additional nuclear power projects up to 2050. The implication of DPP's non-nuclear homeland policy with or without the carbon mitigation target also will be considered. Finally, the potential roles of CCS and expanded nuclear power capacity in cutting the cost of carbon reduction will be discussed.

3. THE MODEL

The multi-sector recursive dynamic general equilibrium model built for this study belongs to the class of Arrow-Debreu model, which assumes markets are perfectly competitive, and the utility function is strictly concave and twice continuously differentiable to ensure the existence and uniqueness of the solution (Arrow and Debreu, 1954). The model is formulated in a series of mixed complementary problems (MCP) (Mathiesen, 1985) using the MPSGE modeling language (Rutherford, 1999). The base year is 2006, and from 2010 onward, it is solved at five-year intervals up to 2050. While this section provides an overview of the model, interested readers may find more details in the Appendix.

3.1 Basic Structure

Three key components in the model are household, producers, and government, as shown in **Figure 3**. The household owns labor and capital, provides them to producers and receives net factor payments from producers. It also receives net transfers from government or abroad as part of disposable income, and then allocates the disposable income for consumption and savings to maximize utility. The household's utility function is represented by a nested constant elasticity of substitution (CES) shown in **Figure 4 (a)**.

Producers (production sectors), on the other hand, transform primary factors (labor and capital) and intermediate inputs (outputs of other domestic or foreign producers) into goods and services, sell them to household, government, other domestic producers, or export them. According to Rutherford and Light (2001), there is also an Armington differentiation between goods produced for domestic and export markets, which is modeled by a constant elasticity of transformation (CET) function, as shown in **Figure 4 (b)**.

This study follows the small open economy assumption, which means that Taiwan is the price taker of tradable goods. The equilibrium prices of different goods and factors are determined by a set of market clearing conditions. In particular, since this study focuses on long-term projection, the exchange rate is allowed to adjust in the direction that clears the foreign exchange market and eliminates the current account imbalance. The model is closed with income balance conditions for household and government.

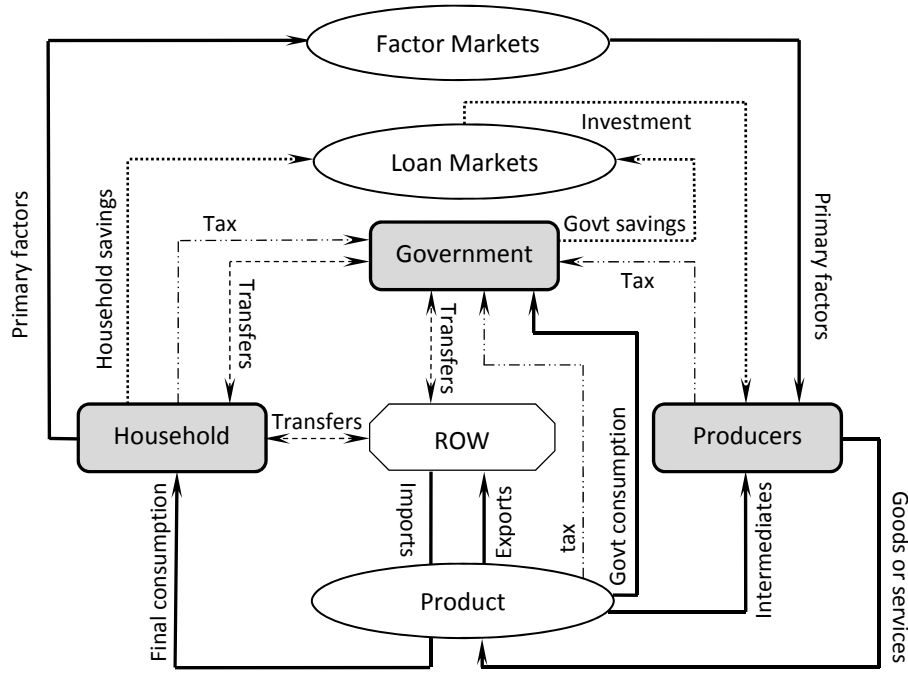


Figure 3. Model structure.

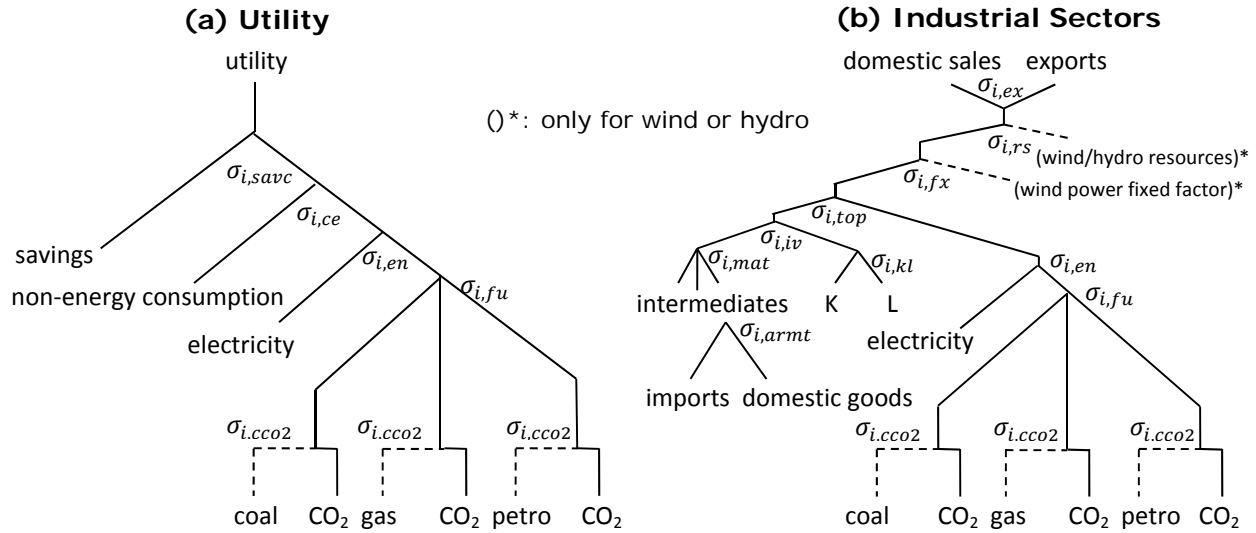


Figure 4. Utility and production functions.

3.2 Dynamic Settings

The nature of recursive dynamics implies that investment is savings driven. In particular, savings provide the funds for investment, and investment compensates the depreciated capital

and forms new capital stock that increases future production capacity of profitable sectors. To avoid a sudden and drastic movement of capital from less profitable sectors to more profitable ones overnight, and account for the observed hysteresis of structural change, for a given period, the capital stock of each sector is represented by a CES aggregation of malleable capital, which can freely move among sectors (in the direction to equalize the capital rental rate), and sector-specific nonmalleable capital.

Based on Dervis *et al.* (1982), the supply of non-malleable capital is determined in a way such that sectors with higher-than-average capital rental rates would get larger shares of investable funds. In addition, the aggregate labor supply is determined by an exogenous labor force growth, and labor is free to move among sectors within the same period. To calibrate the GDP growth to a given projection, in the BAU scenario, the total factor productivity is calibrated to match the projected GDP growth. In policy scenarios, the total factor productivity calibrated from BAU becomes exogenous and GDP becomes endogenous.

3.3 Strategy in Modeling Electricity Sectors

This study disaggregates the electricity sector into six sub-sectors, including coal-fired, gas-fired, oil-fired, nuclear, hydro, and wind power. Because of the variability of wind, it is a non-dispatchable source of power, and its output may not be available when needed. Thus, storage of power is expensive and storage capacity might be limited to hours or days. As a result, even with battery or other storage, wind power is often coupled with other dispatchable generation (Muljadi *et al.*, 2004).

Within the top-down framework, existing studies such as Shelby *et al.* (2008) and McFarland *et al.* (2009) often combine the non-dispatchable and dispatchable generation by a CES function, as shown in **Figure 5a**. While using the CES aggregator with a low substitution elasticity can capture the dependency of a non-dispatchable generation on dispatchable ones, the CES functional form also implies that the reciprocal dependency holds as well. That is, growth in demand for electricity will increase the use of wind power more or less proportionally to other sources, all else equal. While the growth of dispatchable generation will provide more backup capacity, allowing wind power to grow, there is no reason to think that the growth of dispatchable generation should depend on wind power.

This study adopts the following strategy: (1) electricity outputs from different sources are treated as perfect substitutes; (2) for wind power, there is a “fixed factor” that controls its expansion potential, and the fixed factor is proportional to dispatchable generation capacity. More specifically, I consider the case where wind power uses gas-fired and hydro power as backup capacity, as in Kuo (2003) and Mauritzen (2012); and (3) for wind power, the substitution elasticity between the fixed factor and other inputs (and henceforth the fixed factor elasticity) can determine to what extent the growth potential of wind is restricted. With these

treatments, this study can capture the fact that non-dispatchable generation depends on dispatchable generation, but not vice versa. This structure is presented in **Figure 5b**.³

To incorporate natural resource constraints on hydro and wind in this study, the expansions of wind and hydro power are bounded by the levels of hydro and wind resource factors, respectively. The wind resource factor takes into account the highest wind power potential of Taiwan, which is around 3000 MWe (Taiwan Environmental Information Center, 2001). The resource factor for hydro is calibrated in a way such that the BAU projected hydro power output matches the planned expansion projects. These resource factors are inputs to the production functions, and the resource rents go to the representative consumer.

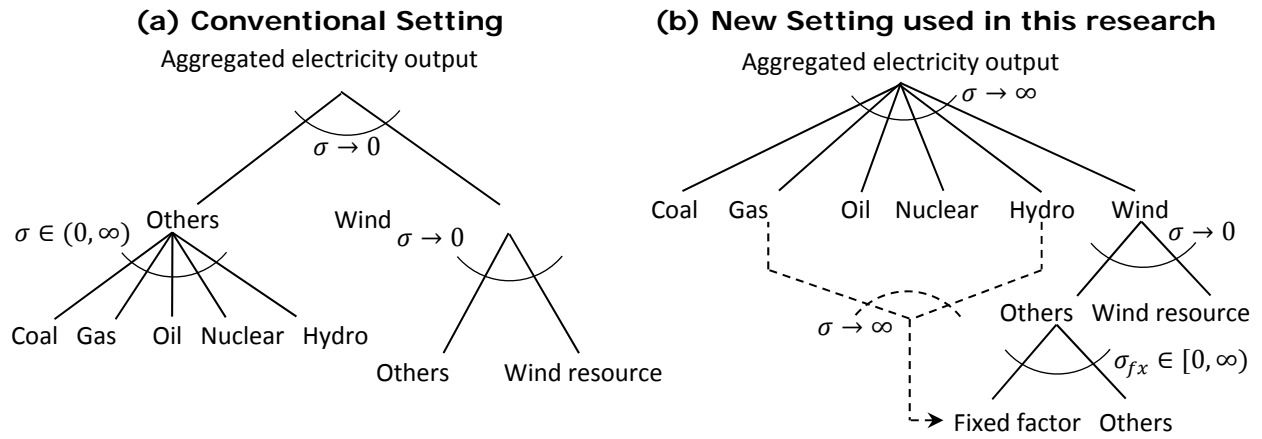


Figure 5. Structure of modeling wind (non-dispatchable) generation.

4. DATA

The data needed for the analysis include: (1) the input-output and national accounting data, which describe the base year economy-wide production and consumption structures; (2) labor force growth projection; (3) the BAU real GDP growth projection; (4) the sectoral energy consumption and the associated CO₂ emissions from combustion; (5) the substitution elasticities characterizing how different inputs can be replaced by others when relative prices change; (6) the output projection of the electricity sector, which also determines the growth potential of each generation technology; (7) the autonomous energy efficiency improvement (AEEI) coefficient, which represents the non-price driven energy efficiency improvement over time; (8) the world price levels for different commodities; and (9) the cost and effectiveness of CCS.

This study classifies the industry into four energy supply sectors and thirteen other industrial sectors, as presented in **Table 3**. In addition to disaggregating the electricity sector, sectors that

³ Note that in equilibrium, the fixed factor could be in surplus, which means that the expansion of dispatchable generation will not be limited by the output level of non-dispatchable one.

fall into the following categories are separated out from others: (1) energy-intensive sectors such as transportation, iron, and chemical industries; and (2) sectors that account for higher shares of GDP, such as electronic and computer, and service sectors.

Table 3. Industrial sectors in the model.

Energy supply sectors		Other industrial sectors	
1	Gas	5	Agriculture
2	Coal	6	Food, alcohol & tobacco
3	Petroleum	7	Textile & clothes
4	Electricity supply	8	Paper products
4-1	coal-fired	9	Chemical industry
4-2	gas-fired	10	Plastic & rubber
4-3	oil-fired	11	Cement & non-metallic
4-4	nuclear	12	Iron
4-5	hydro	13	Electronic & computer
4-6	wind	14	Other manufacturing
		15	Construction
		16	Transportation
		17	Service

The 17-sector Social Accounting Matrix (SAM), which summarizes the input-output and national accounting data of Taiwan, is compiled based on the input-output table published by the Directorate-General of Budget, Accounting and Statistics (DGBAS, 2011), Taiwan's chief statistics and accounting agency. A simplified representation for the input structure of production sectors is presented in **Table 4**.

Table 4. Input structure of industrial sectors.

	Gas	Coal	Petro*	Electricity	Materials	Value-added
Gas	27.31%	1.21%	27.05%	0.86%	17.56%	26.00%
Coal	0.06%	10.81%	2.87%	1.96%	67.29%	17.01%
Petroleum	0.89%	0.00%	79.34%	2.90%	4.49%	12.38%
Electricity	17.76%	17.71%	12.51%	10.88%	8.29%	32.86%
Agriculture	1.57%	0.52%	5.53%	0.98%	47.36%	44.05%
Food, alcohol & tobacco	0.12%	0.01%	1.17%	1.28%	72.73%	24.69%
Textile & clothes	0.12%	0.00%	1.83%	2.83%	75.75%	19.47%
Paper products	0.14%	0.12%	2.56%	4.08%	71.73%	21.37%
Chemical industry	0.32%	0.04%	13.73%	2.67%	70.72%	12.52%
Plastic & rubber	0.12%	0.02%	1.16%	2.24%	76.01%	20.44%
Cement & non-metallic	1.37%	2.75%	5.32%	4.48%	60.61%	25.49%
Iron	0.32%	2.60%	0.94%	2.05%	80.52%	13.57%
Electronic & Computer	0.11%	0.00%	0.13%	1.23%	75.14%	23.40%
Other manufacturing	0.12%	0.05%	0.78%	1.01%	75.09%	22.95%
Construction	0.02%	0.00%	1.14%	0.32%	69.41%	29.12%
Transportation	0.02%	0.00%	23.46%	0.44%	44.28%	31.80%
Service and other public utility	0.14%	0.00%	0.86%	0.99%	27.97%	70.04%

*For petroleum sector, crude oil is excluded from the calculation of combustion emissions since it is not combusted.

While this study draws the labor force growth projection from the Council for Economic Planning and Development (CEPD, 2011), the BAU real GDP growth projection is from DGBAS (2012), which is 1.66% for 2012. For later years where the projection is not available, it is assumed that the annual real GDP growth rate will be 3.0% from 2013 to 2019, 2.5% from 2020 to 2024, 2.0% from 2025 to 2034, 1.5% from 2035 to 2045, and 1.0% from 2046 onward. Sensitivity analyses with a higher or a lower GDP growth rate will be provided later. The substitution elasticities are based on Paltsev et al. (2005) and Rausch et al. (2009). The sectoral combustion emissions data are from the report published by the Bureau of Energy (Bureau of Energy, 2010), as presented in **Table 5**.

Table 5. Base year sectoral combustion emissions.

Sector	Sector mapping	kt-CO ₂
Energy supply sectors	1–4	169404
Agriculture	5	1630
Mining, manufacturing & construction	6–15	42655
Transportation	16	36406
Service	17	4125
Household		5046

Source: Bureau of Energy (2010).

The emissions data in the report, however, only disaggregate the industry into five sectors. To find CO₂ emissions with a higher sectoral resolution, I first derive the energy consumption by each of the seventeen sectors, and then multiply the consumption level by the corresponding emissions coefficient, which is also presented in Bureau of Energy (2010). To find each sector's energy consumption, for non-electricity sectors, I use each sector's energy consumption value presented in the SAM to decompose the aggregated energy consumption since each sector's energy consumption level (in thermal unit) is not available; and for the electricity sector, I draw the energy consumption (in thermal unit) of each generation type from the Energy Statistics Year Book (Bureau of Energy, 2011d). The results are presented in **Table 6**.

I consider the case that in the BAU, the lost generation capacity due to the phase out of existing three nuclear power plants will be replaced by gas-fired generation, following the government's plan. In addition, the AEEI coefficient, which is 0.75% per year, is drawn from Yang *et al.* (1996). Further, I assume that the world crude oil price, which is exogenous to the model because of the small open economy assumption, will grow at the rate of 10% per period (i.e., every five years) based on the median projection for the future crude oil price presented by EIA (2010). Lastly, this study considers cases where CCS is viable on fossil-based generation. The engineering data of CCS are from Ansolabehere *et al.* (2007), which presents a cost estimate of US\$40.36 per ton of CO₂ captured and stored with a capture rate of 89%. A sensitivity analysis with a wider range of CCS cost will be presented later.

Table 6. Base year sectoral combustion emissions.

#	Sector	Output (million NT\$)	CO ₂ Emissions (ton)	Sectoral CO ₂ share (%)
1	Gas	61229	3699842	1.43%
2	Coal	39086	4245036	1.64%
3	Petroleum	1037380	5143446	1.98%
4	Electricity			
4-1	electricity: coal	219335	124950573	48.19%
4-2	electricity: gas	145841	16530933	6.38%
4-3	electricity: petro	83535	14834170	5.72%
4-4	electricity: nuclear	44232	0	0.00%
4-5	electricity: hydro	8874	0	0.00%
4-6	electricity: wind	308	0	0.00%
5	Agriculture	527207	1630000	0.63%
6	Food, alcohol & tobacco	575770	381918	0.15%
7	Textile & clothes	499244	467183	0.18%
8	Paper products	187798	369578	0.14%
9	Chemical industry	1932794	13166203	5.08%
10	Plastic & rubber	461438	344273	0.13%
11	Cement & non-metallic	262505	5188649	2.00%
12	Iron	1179257	19090665	7.36%
13	Electronic & Computer	4107442	524596	0.20%
14	Other manufacturing	3253568	2377750	0.92%
15	Construction	1382727	744185	0.29%
16	Transportation	820902	36406000	14.04%
17	Service and other public utility	11717928	4125000	1.59%
	Household		5046000	1.95%

5. POLICY IMPACTS

The scenarios considered include both policy and technology dimensions. In addition to BAU, various combinations of non-nuclear policy, low-carbon target, and the viability of CCS on fossil-based generation are presented below.

5.1 Scenarios

In the BAU scenario, there are no policy interventions, and the existing three nuclear power plants of Taiwan will phase out in 2018, 2021, and 2024, respectively, when they reach the end of their designed life spans. Since the model runs in five-year intervals from 2010 onward, this scenario is represented by assuming the No. 1 nuclear power plant, with the capacity of 1272 MWe, will phase out in 2020, the No. 2 and No. 3 nuclear power plants, with the capacities of 1970 MWe and 1902 MWe, respectively, will both phase out in 2025. Lastly, the Longmen nuclear power station, with the capacity of 2750MWe, is assumed to join the grid in 2015.

In the non-nuclear policy scenario, everything is the same as the BAU scenario except that the Longmen Nuclear Power Station will never operate. In the low-carbon policy scenario, the Longmen Nuclear Power Station will be in service from 2015 onward. The government will achieve its CO₂ reduction target, which aims at cutting the emissions to half of the 2000 levels by 2050 (see Section II for details), by levying a hypothetical carbon tax on all sources of domestic

combustion emissions. The carbon tax revenue goes to the household as a lump-sum transfer. In the non-nuclear and low-carbon policies scenario, both the non-nuclear and low-carbon targets will be implemented.

Two additional scenarios with different technology and policy assumptions are considered: non-nuclear and low-carbon policies with CCS, and low-carbon with CCS and tripled-nuclear capacity. The latter allows tripling the nuclear power capacity by 2050 relative to the BAU level of 2015, while the existing four nuclear power stations of Taiwan are in service, when the low-carbon target is pursued. While both scenarios represent optimistic projections of CO₂ mitigation opportunity created by cutting fossil-based emissions, the later scenario presents a counterfactual case to show the potential role of nuclear power if the low-carbon target is the policy priority. The scenarios and their policy and technology assumptions are summarized in **Table 7**.

Table 7. Policy and technology assumptions of each scenario.

Scenario	Policy and technology assumptions
BAU	The existing three nuclear power plants in Taiwan would phase out as they reach the end of their life spans by 2024, and the Longmen Nuclear Power Station would join the grid starting in 2015.
Non-nuclear	The existing nuclear plants would phase out at the end of their lifetimes, and the Longmen plant would never operate.
Low-carbon	The Longmen plant would operate starting in 2015 and the government would impose the carbon policy from 2015 onward. The carbon tax revenue goes to the household as a lump-sum transfer.
Both	Both non-nuclear and low-carbon policies are enforced.
Both with CCS	Both non-nuclear and low-carbon policies are enforced, and CCS on fossil-based generation is available.
Low-carbon with CCS and tripled nuclear	The low-carbon policy will be enforced, the capacity of nuclear power is allowed to tripled compared to its 2015 level under the BAU scenario, and CCS on fossil-based generation is available.

5.2 Business-As-Usual Projection

As shown in **Figure 6a**, the projected CO₂ emissions of BAU would increase by around 83.4% in 2050 compared to 2010 levels, which is lower than the projected GDP growth during the same period due to the improvement of AEEI and the expansion of more energy efficient sectors as world fuel prices continue to increase in the long run. Nevertheless, under the BAU scenario, although CO₂ emissions intensity (CO₂ emissions per dollar GDP) decreases, CO₂ emissions per capita will be doubled from 12.6 ton/person-year to 25.6 ton/person-year, as shown in **Figure 6b**. Figure 6a also shows that the 2050 CO₂ target of 50% below 2000 levels requires a 79.9% cut from the BAU level, reducing emissions to around 5.2 tons per capita per year.

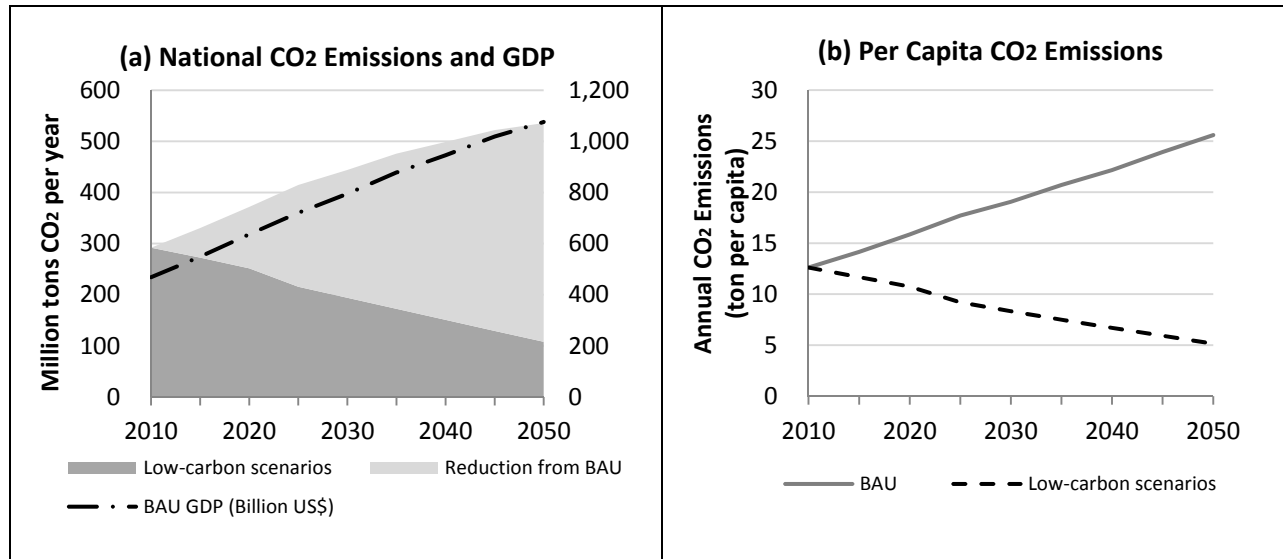


Figure 6. Projections for Taiwan's national and per capita CO₂ emissions.

5.3 GDP and Welfare

The changes in real GDP relative to the BAU level are presented in **Figure 7**. The results show that negative impact on real GDP under the non-nuclear policy scenario is relatively small. This is because the BAU scenario takes into account the government's plan, which will only operate the Longmen Nuclear Power Station once ready without adding any additional nuclear capacity in later years. Under this benchmark, with the non-nuclear scenario, the reduced nuclear capacity only comes from excluding the Longmen Nuclear Power Station from joining the grid, and this is why the GDP impact is mild if the non-nuclear policy were carried out alone. For other countries where the BAU nuclear power projects are unrestricted, enforcing non-nuclear policies may have a greater negative impact on their GDPs.

Implementation of the low-carbon policy would have a much significant impact on Taiwan's economy, and if CCS is not feasible, with both non-nuclear and low-carbon policies, the real GDP will decrease by around 20.5% relative to the BAU projected GDP level in 2050. Alternatively, under the same scenario, the implementation of CCS on fossil-based generation, when viable, has the potential of lowering the negative GDP impact down to about 9.5% by reducing the carbon penalty of fossil-based generation when the shadow carbon price exceeds the cost of CCS. Lastly, the negative GDP impact under the low-carbon target could be lowered to around 5.9% if the capacity of nuclear power were tripled, as shown in the result for the low-carbon with CCS and tripled-nuclear capacity scenario. Figure 7 also shows that while changes in welfare (measured in terms of the equivalent variation EV) are similar to those for GDP, the negative impacts are somewhat larger due to the fact that net exports, which are part of GDP, would increase if the low-carbon policy were in place. With that policy, the decrease in fossil fuel imports is the dominant factor that contributes to the increase in net exports, and the increase in net exports explains why the GDP impact is lower than the welfare impact.

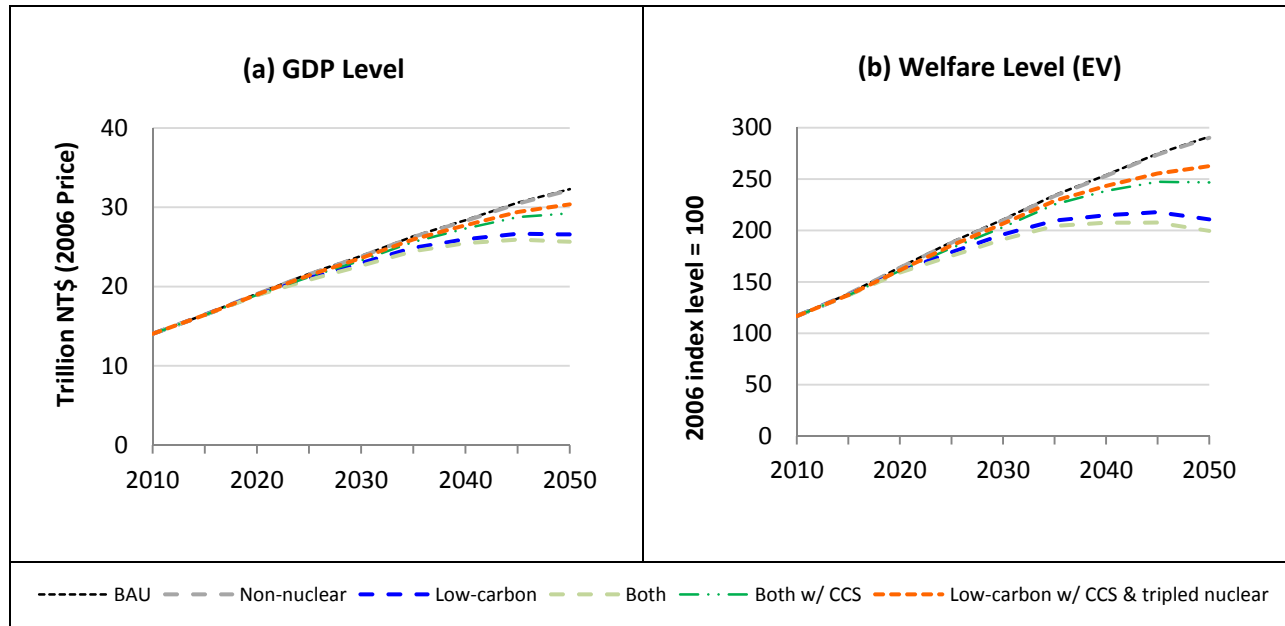


Figure 7. GDP and welfare levels under different scenarios.

5.4 Additional CO₂ Emissions of Non-nuclear Scenario

Under the non-nuclear policy scenario, fossil-based generation will replace part of the lost electricity output, and this will lead to an increase in Taiwan's national CO₂ emissions, as shown in **Figure 8a**. While electricity sectors, especially coal-fired power, will contribute to most of the additional emissions, a slight increase in emissions from other industrial sectors reflects that electricity input is substituted by other fossil-based energy input. **Figure 8b** shows that Taiwan's national CO₂ emissions may increase by around 4.5% relative to BAU levels from 2035 onwards. The emissions increase is not trivial, which suggests that when pursuing the non-nuclear policy, it is also important to consider effective measures that could curb CO₂ emissions.

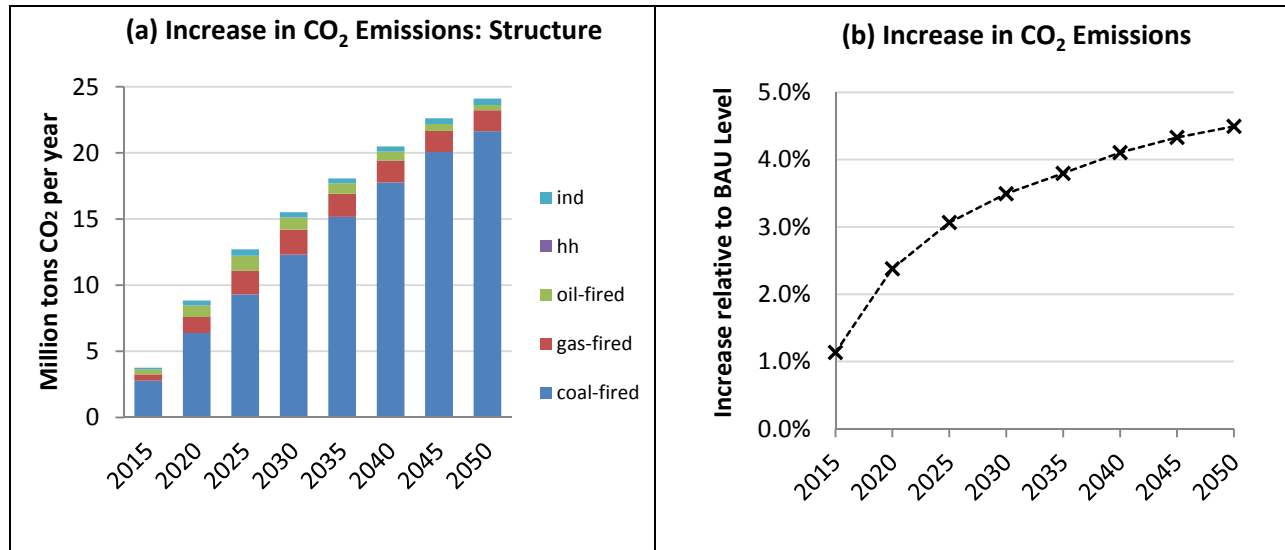


Figure 8. Increase in CO₂ emissions relative to BAU levels under the non-nuclear scenario.

5.5 Carbon Price

Figure 9 shows that under the low-carbon policy scenario, the carbon price will increase from 23 US\$/ton-CO₂ in 2015 to 226 US\$/ton-CO₂ in 2030, and will finally exceed 1800 US\$/ton-CO₂ in 2050 if CCS on fossil-based generation is not available. The carbon price under the scenario of non-nuclear and low-carbon policies will be even higher since there will be more emissions from fossil-based generation, which bid up the price. This study also finds that if CCS were viable (at the cost of US\$ 40.36 per ton of CO₂ captured and stored and with a 89% reduction rate), it could significantly reduce the carbon price. Nevertheless, even with CCS, the carbon price may still exceed 1100 US\$/ton-CO₂ in 2050. While expanding nuclear capacity beyond the Longman nuclear project to replace fossil-based generation is unlikely in Taiwan due to safety and waste disposal concerns, Figure 9 also shows that tripling the nuclear power capacity on top of the CCS option could further reduce the carbon price down to around 781 US\$/ton-CO₂ in 2050. In short, if expanding nuclear power capacity is not an option, then carbon abatement cost would be much higher.

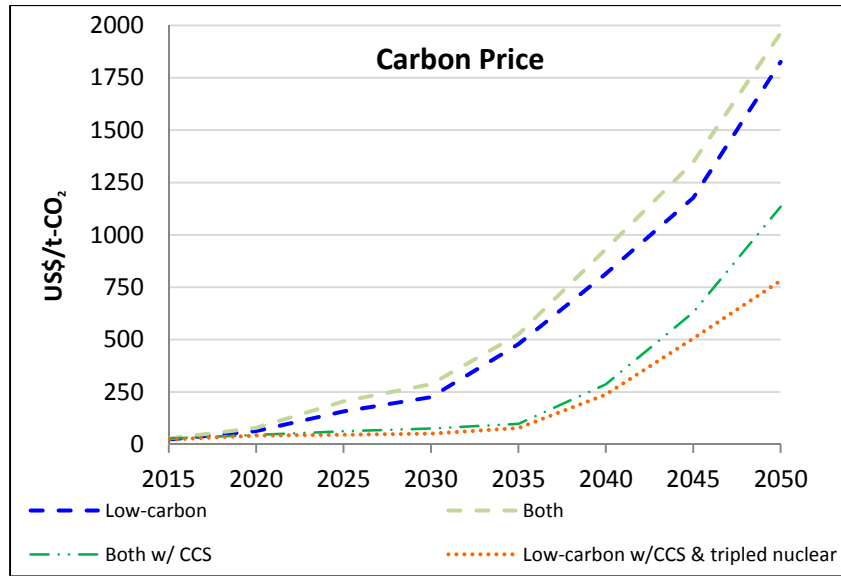


Figure 9. Carbon prices under different scenarios.

5.6 Sectoral Impact

Compared to the non-nuclear policy, enforcement of carbon policy has a much larger sectoral impact (change in sectoral output), as shown in **Figure 10**. Note that with the small-open economy assumption, the fact that Taiwan has to import almost all of its energy supply suggests that it has to bear most of the burden from the implementation of the hypothetical carbon tax since energy supply from the rest of the world is highly elastic. In particular, sectors that would incur higher negative impacts are those: (1) that provide fossil-based products including coal, petroleum, and gas; and (2) that depend more on high-carbon content inputs (and thus have higher levels of combustion emissions per unit of output) such as the chemical industry, iron industry, cement and non-metallic industry, coal-fired generation, etc., as shown in Table 4.⁴ Although adopting CCS on fossil-based generation allows a higher level of electricity output compared to no CCS cases, it does not negate the effects of enforcement of carbon policy. Changes in relative prices that favor the expansion of less energy-intensive sectors will, over the long run, cause more production factors to move to sectors that incur fewer carbon penalties. Such sectors would avoid carbon penalties directly (through combustions emissions) or indirectly (through the use of electricity) such as service sectors and electronic and computer industry. Lastly, Figure 10 shows that with the low-carbon target, the sectoral impacts could be further reduced when the nuclear power capacity is allowed to triple by 2050, which provides more carbon-free electricity output.

⁴ See Subsection 5.8 and Figure 10 for the case of the negative impact on coal-fired generation.

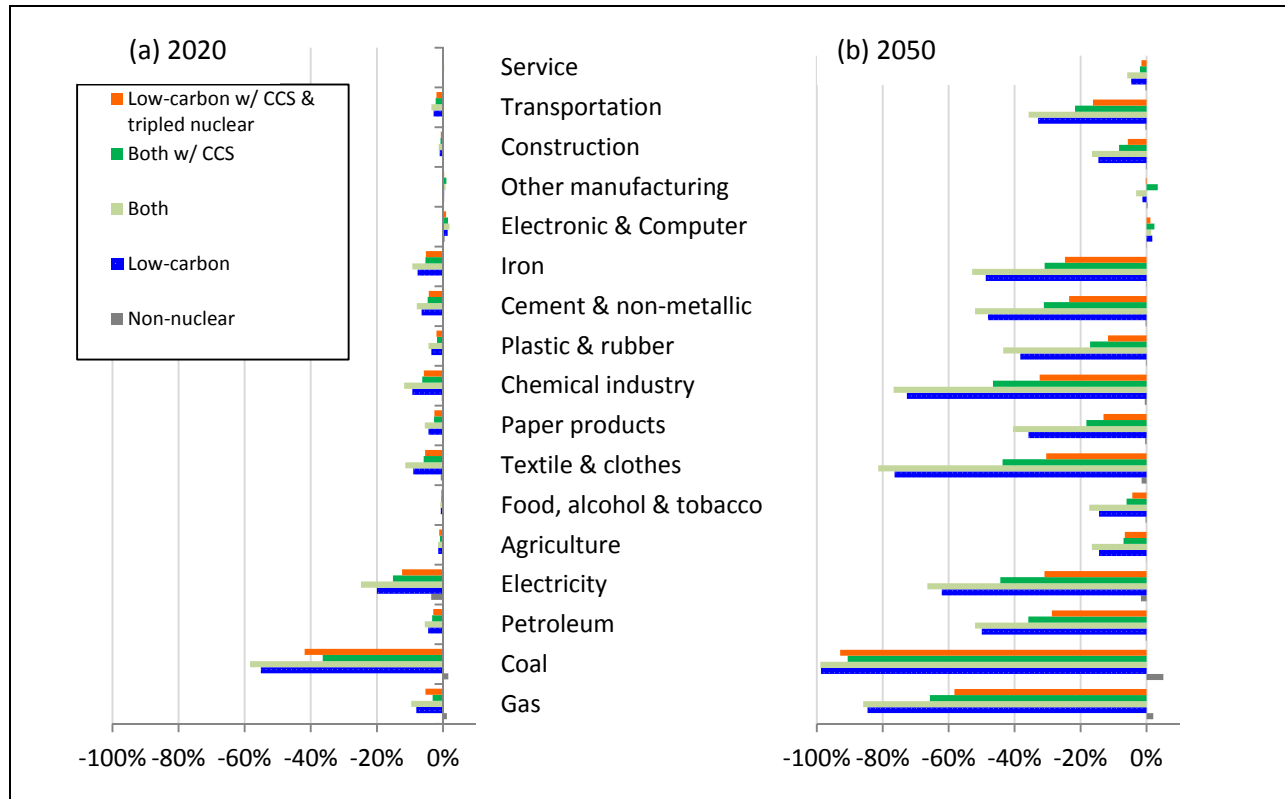


Figure 10. Change in sectoral output under different scenarios.

5.7 Changes in Net Exports and the Implication for Carbon Leakage

Figure 11 presents the changes in sectoral net exports. For simplicity, only the results for the scenario of non-nuclear and low-carbon policies are presented since the impacts under this scenario are most significant. Note that the model has taken into account the case where outputs from electricity, construction, transportation, and service sectors are non-tradable. An interesting finding is that the net exports of sectors with larger carbon footprints will decrease significantly compared to those of other sectors, due to the increase in imports and/or the decrease in exports. Prominent examples are cases for the chemical industry, cement and non-metallic industry, and iron industry, which together accounted for almost 15% of Taiwan's national CO₂ emissions in 2006 (see Table 6). This suggests that CO₂ emissions abatement in Taiwan results in carbon leakage since imported carbon-intensive products from countries without carbon policies can replace the domestic ones, and exported carbon-intensive products to no-policy countries can be replaced by those produced locally in the no-policy countries. However, if the rest of the world also imposes carbon reduction policies, one could expect that the cost for Taiwan to pursue a non-nuclear and low-carbon world will be higher since the imports of carbon-intensive products will become more expensive as well.

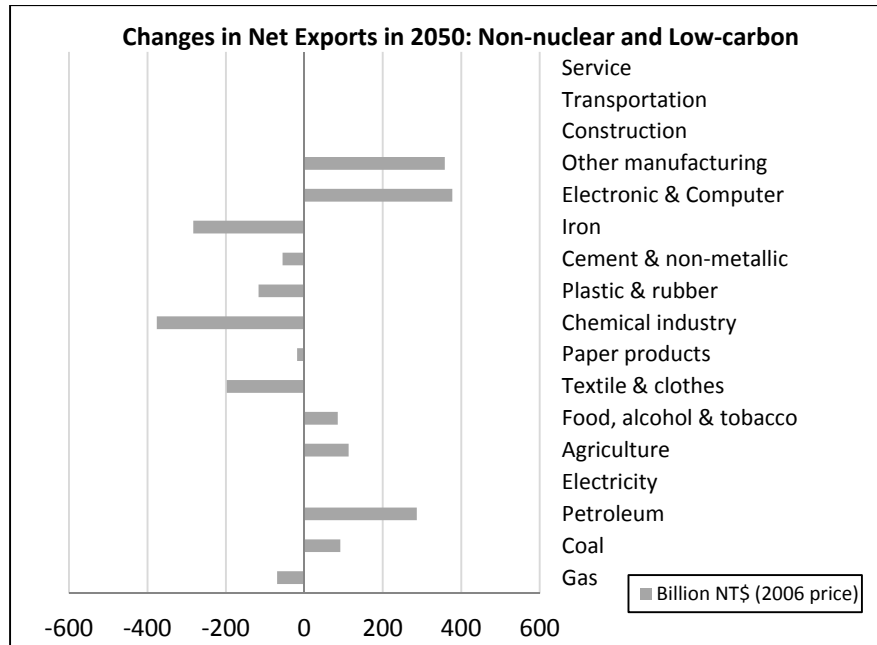


Figure 11. Changes in net exports.

5.8 Electricity Sector and Sensitivity Analyses

This study finds that, if the non-nuclear policy were enforced alone, wind power will provide a tiny fraction of the electricity supply—around 0.4% in 2050 compared to the BAU level of 0.37%, as shown in **Figure 12**. In fact, fossil-based generation will play the main role in compensating part of the lost capacity of Longmen Nuclear Power Station since the expansion of hydro power is more restricted due to the resource constraint.

With the carbon policy, if CCS is not available, coal-fired power has to be completely phase-out 20 years from now, and other generation options, especially gas-fired power, will provide around three quarters of electricity supply. As shown in Figure 12, when both policies were adopted, gas-fired power will account for almost 89.5% of electricity supply in 2050, and the rest will be supplied by hydro power (7.2%) and wind power (3.3%).

Figure 12 also shows that with the carbon constraint, while gas-fired power will continue to provide the highest output level among other generation when CCS is viable, there will be significant roles left for coal-fired and oil-fired power in later years after the introduction of CCS between 2020 and 2025, when the carbon price per ton exceeds US\$40 and makes CCS economically feasible. Although under the carbon policy, the higher level of national electricity supply when CCS is viable also suggests a lower negative impact on GDP, the electricity supply may still decrease by around 43.6% compared to the BAU level. Finally, if tripling the nuclear power capacity by 2050 (compared to the 2015 level) is viable, nuclear power would provide almost half (46.9%) of electricity output in 2050, and it will replace a lot of electricity output from fossil-based generation with CCS (especially coal fired power with CCS), and also increase

the national electricity output by 23.2%, compared to the scenario when both policies are enforced and CCS is viable. In short, if nuclear power will not be an option, then developing more electricity-efficient industries will be a crucial step toward a low-carbon future.

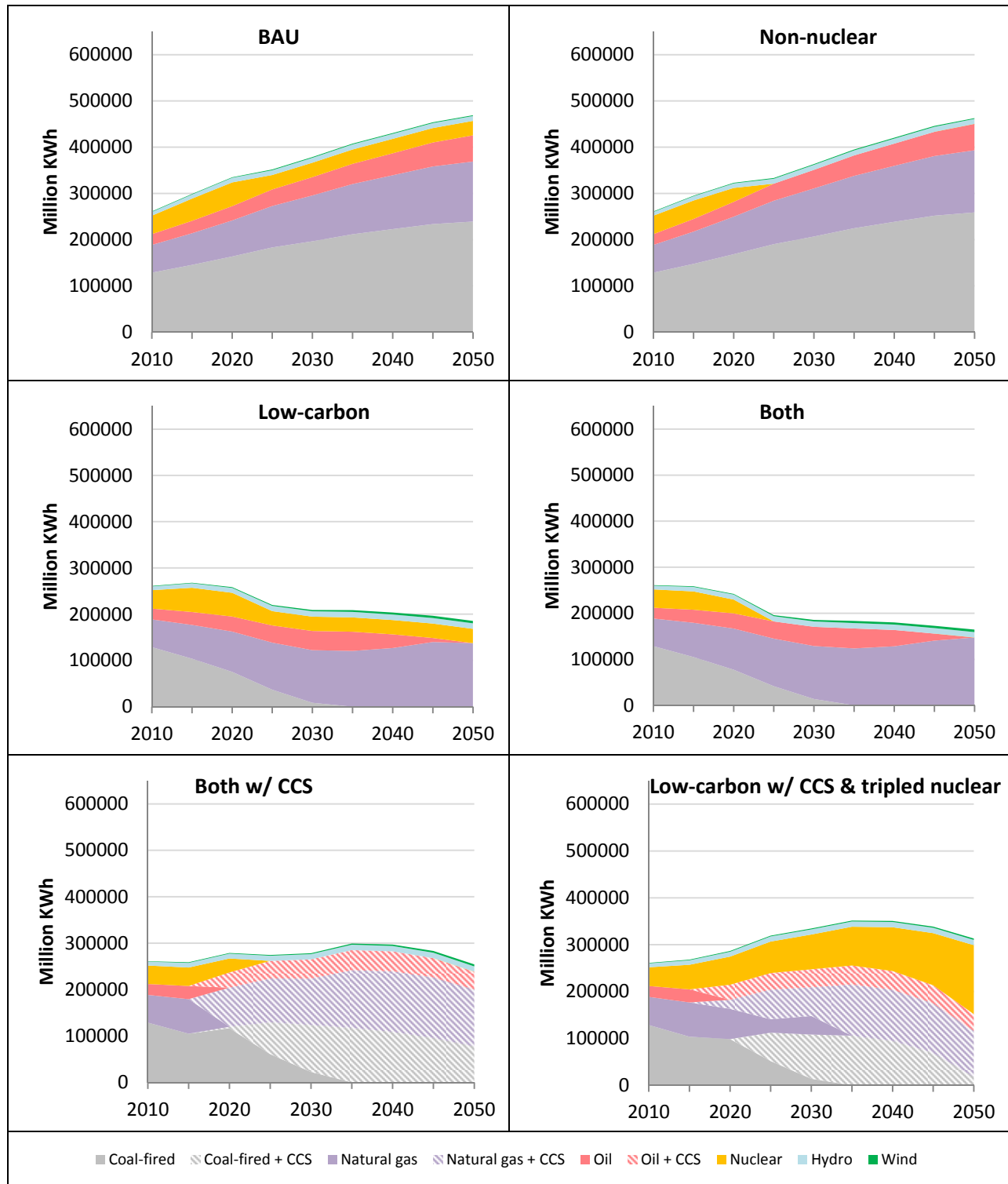


Figure 12. Output structures of different generation types.

Note that this study considers the dependency of wind power on other dispatchable generation, including gas-fired and hydro power. If both policies were in place and CCS is not viable, wind power may provide 5370 million KWh/year in 2050. It represents the middle projection of more extreme cases. More specifically, as shown in **Figure 13**, in 2050, wind power output under the scenario of non-nuclear and low-carbon policies may range from 2573 million KWh/year (1.6% of national electricity supply), where the expansion of wind power is completely limited by the scale of its back-up capacity,⁵ to 8383 million KWh/year (5.0% of national electricity supply), where the expansion of wind power is less or no longer dependent on the back-up capacity, and all potential wind capacity of Taiwan—3000 MWe—is exhausted.⁶

Figure 14 provides a sensitivity analysis on GDP impact with various CCS costs. It shows that for fossil-based generation, even under a relatively optimistic scenario with a CCS cost of only US\$ 20 per ton of CO₂ captured and stored, GDP may still decline by around 9.2% relative to the BAU level in 2050 if both policies were enforced—a result again confirming that to achieve the very stringent emissions cut, converting Taiwan’s industrial structure into a less energy-intensive one and limiting the expansion of fossil-based generation are necessary. These findings remain unchanged even if the CCS on power sector can reach a hypothetical CO₂ capture rate of almost 100% (see the sensitivity analysis in Appendix A3). Lastly, **Figure 15** shows how the uncertainty in the BAU GDP growth rate projection may affect the CO₂ emissions of Taiwan, and, in turn, determine the emissions reduction efforts, as reflected by the shadow carbon price shown in **Figure 16**. This study finds that the carbon price may still exceed US\$1400/ton-CO₂ in 2050 under the lower GDP growth rate scenario, if CCS is not viable, and both the non-nuclear and low-carbon policies were carried out.

⁵ This is modeled by a zero fixed factor elasticity of wind power ($\sigma_{fx} = 0$). See Figure 4 and Figure 13.

⁶ The estimate for the average wind power capacity factor in Taiwan ranges from 0.29 to 0.37 (Kuo, 2003; Taiwan Panorama, 2011). In this study, the capacity factor used is 0.32, which is the estimated break-even level for wind power to become economically viable (Hung, 2008).

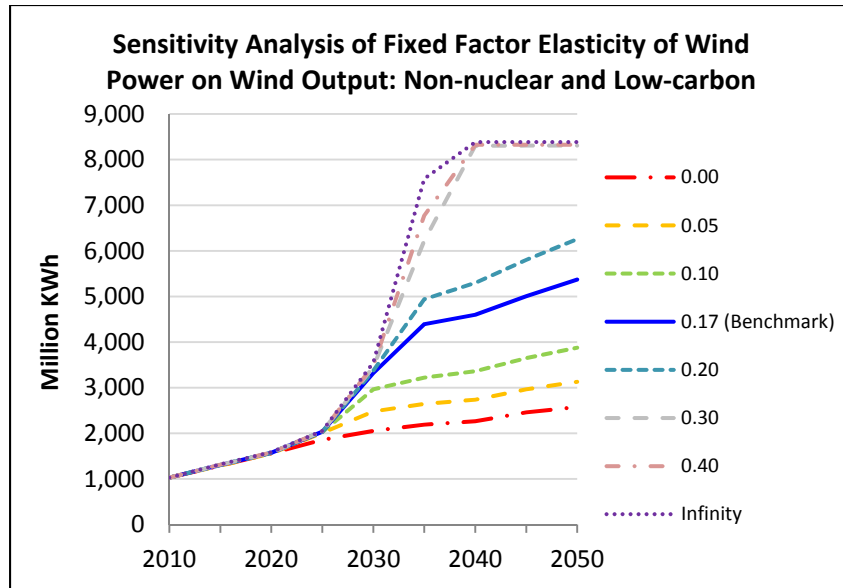


Figure 13. Wind power output under different fixed factor elasticity.

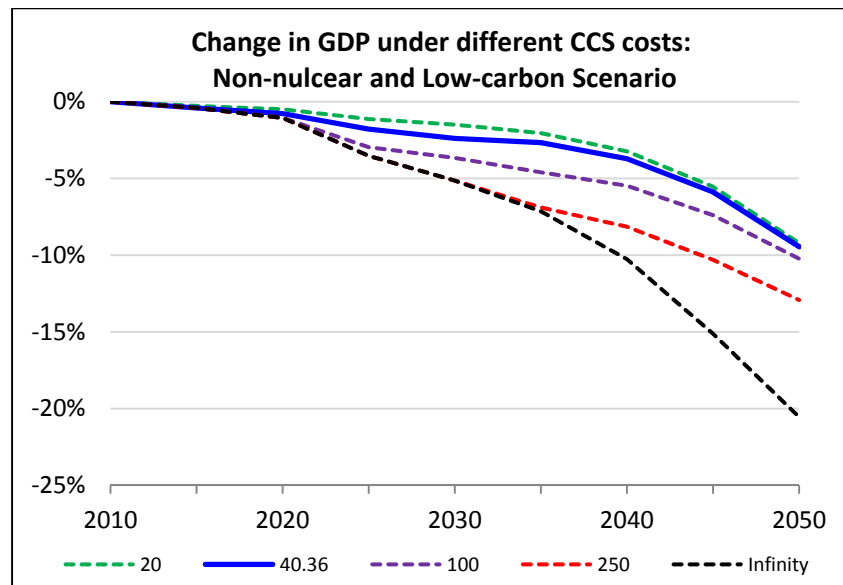


Figure 14. Change in GDP under different CCS costs (US\$/ton-CO₂).

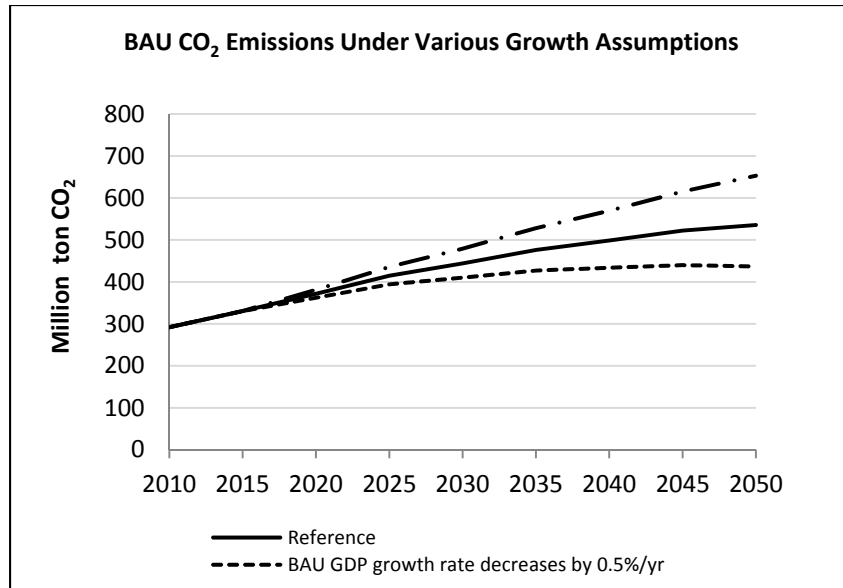


Figure 15. BAU CO₂ emissions projections under different GDP growth trajectories.

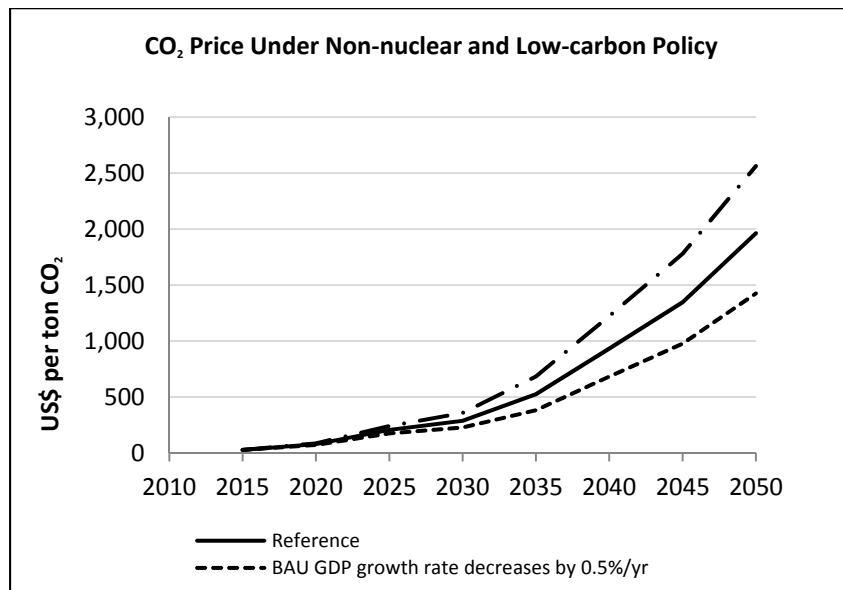


Figure 16. Carbon prices for non-nuclear and low-carbon scenario under different assumptions for BAU GDP growth.

6. CONCLUSIONS

Before the Fukushima nuclear accident, the pressure to cut CO₂ emissions brought nuclear power into the spotlight. After the accident, however, people in Taiwan have seriously

considered non-nuclear options since, much like Japan, Taiwan faces threats of devastating earthquakes and tsunamis.

In this study, I provide an economy-wide analysis for Taiwan under the low-carbon growth path with or without the nuclear option, and improve the modeling for the dependency of non-dispatchable generation (wind power in particular) on other dispatchable generation. Although expansion of nuclear power reduces the negative economic impact in cutting CO₂ emissions and lowers the dependence of Taiwan on imported fossil fuels, it would require the assurance that nuclear disasters such as the one at Fukushima could be avoided, and that disposal of nuclear wastes is no longer an issue. In reality, since both nuclear safety and waste disposal are great concerns in Taiwan, which make nuclear expansion seem less likely, I also investigate the implication of carrying out the non-nuclear and low-carbon environment, and I find that pursuing a low-carbon target without a nuclear option could be expensive. Although the adoption of CCS on fossil-based generation, when viable, has the potential to lower around half of the negative GDP impact, for the demand side, a huge change in industrial structure is still required to achieve this goal, as both carbon-intensive and energy-intensive activities will be discouraged. For the supply side, the electricity output will decrease significantly relative to the BAU level—an outcome reflecting that, in Taiwan, expansions of renewable generation such as hydro and wind are limited by resources and technological constraints.

The analysis models Taiwan as a small open economy. One result of this is that there are large effects on trade. While this study does not explicitly model the rest of the world, the likely implication is carbon leakage. If the rest of the world were also to pursue low-carbon policies, there would be fewer channels for Taiwan to reduce its CO₂ mitigation costs through trade.

While for Taiwan, carrying out the low-carbon target without the nuclear option could be expensive, the costs may be lowered through opportunities such as purchasing cheaper emissions allowances from abroad whenever possible, which could be an extension for future research. Another extension is to consider the risk of nuclear accident in the analysis when the focus is on providing a comprehensive cost-benefit analysis for the operation of nuclear power. Finally, future research can consider the potential roles of technological breakthroughs, such as the innovation of more efficient yet cheaper solar panels, which allows much significant solar power utilization, and the exploitation of geothermal energy, which, in Taiwan, may provide almost ten times the capacity of Longmen Nuclear Power Station according to recent research funded by National Science Council (Radio Taiwan International, 2011). Technology innovations, once viable, may also lower the cost of pursuing the non-nuclear and low-carbon environment.

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APPENDIX

A1. Basic Model Structure

The problem for household's utility maximization is presented in (1), where h is the household disposable income, pa_i is the price of Armington good i , which is the CES aggregation of domestic and imported goods, c_i , $pinv$, and s are private consumption, price of investment, and private savings, respectively.

$$\max_{c_i, s} w(c_i, s) \quad s.t. \quad h = \sum_i pa_i \cdot c_i + pinv \cdot s \quad (1)$$

In addition, h includes factor payment, net foreign transfer, and net government transfer as follows:

$$h = \sum_n pf_n \cdot f_n + pfx \cdot (ftrh - htrf) + pw \cdot (gtrh - dt) \quad (2)$$

In (2), pf_n is the rental price for primary factor n ($n \in \{\text{labor, capital}\}$), f_n is the factor supply, and $gtrh$, $ftrh$, $htrf$, dt , pw , and pfx are government transfer to household, foreign transfer to household, household transfer to abroad, direct tax, price index for welfare, and price index for foreign exchange, respectively. The first order condition for utility maximization can be formulated as the MCP problem presented in (3), and consumption and savings can be derived by Shephard's Lemma as shown in (4):

$$e(pa_i, pinv) \geq pw ; w \geq 0 ; [e(pa_i, pinv) - pw] \cdot w = 0 \quad (3)$$

$$c_i = h \frac{\partial e}{\partial pa_i} ; s = h \frac{\partial e}{\partial pinv} \quad (4)$$

The producer's profit maximization problem is written as:

$$\max_{x_i, e_i, id_j, fd_n} \pi_i = px_i \cdot x_i + pxf_i \cdot e_i - \psi_i(pa_j, pf_n, x_i, e_i) \quad (5)$$

In problem (5), π_i , px_i , x_i , pxf_i , e_i , $\psi_i(\cdot)$, and id_j denote profit, price of domestic good, domestic good, domestic price of foreign (exported) good, export, cost function, and demand for intermediate inputs, respectively. The producer's optimizing behavior requires the following zero-profit condition:

$$\frac{\partial \psi_i}{\partial x_i} \geq px_i ; x_i \geq 0 ; \left[\frac{\partial \psi_i}{\partial x_i} - px_i \right] \cdot x_i = 0 \quad (6)$$

$$\frac{\partial \psi_i}{\partial e_i} \geq pxf_i ; e_i \geq 0 ; \left[\frac{\partial \psi_i}{\partial e_i} - pxf_i \right] \cdot e_i = 0 \quad (7)$$

Conditions (6) and (7) determine the outputs of domestic good x_i and exported good e_i . Note that the domestic price of foreign good, pxf_i , can be decomposed as:

$$pxf_i = pfx \cdot pxfex_i \quad (8)$$

where pfx is the price of foreign exchange, and $pxfex_i$ is the foreign price of foreign good i . This study follows the small open economy assumption, which means that Taiwan is the price taker of tradable goods, and because of that, $pxfex_i$ is exogenous to the model. Similar to (4),

the producer's optimization behavior also determines the demand for intermediate goods (which are Armington goods) id_j and the demand for factors fd_n :

$$id_j = x_i \frac{\left(\frac{\partial \psi_i}{\partial x_i}\right)}{\frac{\partial \psi_i}{\partial pa_j}} + e_i \frac{\left(\frac{\partial \psi_i}{\partial e_i}\right)}{\frac{\partial \psi_i}{\partial pa_j}}; fd_n = x_i \frac{\left(\frac{\partial \psi_i}{\partial x_i}\right)}{\frac{\partial \psi_i}{\partial pf_n}} + e_i \frac{\left(\frac{\partial \psi_i}{\partial e_i}\right)}{\frac{\partial \psi_i}{\partial pf_n}} \quad (9)$$

The equilibrium level of imported good m_i is determined in a way such that no further arbitrage opportunity exists, as shown in Condition (10):

$$c_m^i = pfx \cdot pxfex_i \cdot (1 + tarfr_i) - pxf_i \cdot (1 + \overline{tarfr_i}) \geq 0; m_i \geq 0; c_m^i \cdot m_i = 0 \quad (10)$$

where $tarfr_i$ is the tariff rate with an initial value $\overline{tarfr_i}$.

The income balance of household is just the constraint of (1), and the government's income balance condition can be written as:⁷

$$pw \cdot idt + pw \cdot dt + pfx \cdot ftrg = \sum_i pa_i \cdot g_i + pw \cdot gtrh + pfx \cdot gtrf + pinv \cdot sg \quad (11)$$

where the left side represents the government revenue where idt , dt , and $ftrg$ are the sums of indirect tax, direct tax, and foreign transfer to the government, respectively, and the right side is the government expenditure where g_i , $gtrh$, $gtrf$, and sg are government consumption, transfer to household, transfer to abroad, and government savings, respectively. Finally, pw , the Hicksian welfare index, is chosen to be the numeraire of the model.

A2. Dynamic Settings

The capital stock of each sector is represented by a CES aggregation of malleable capital (with a proportion of $\phi = 0.9$), which can freely move among sectors within a given period, and sector-specific nonmalleable capital (with a proportion of $1 - \phi$). The capital formation of malleable capital can be described as:

$$K_{t+1} = I_t + (1 - \delta) \cdot K_t \quad (12)$$

where K_t , I_t , and δ are capital stock, investment, and depreciation rate, respectively. While the capital formation of nonmalleable capital shares a similar mechanism shown in (12), it becomes sector-specific. The supply of non-malleable capital is determined by equation (13) presented by Dervis et al. (1982). In equation (13), the sectoral share of investable fund $si_{i,t}$ will be determined in a way such that it is proportional to the sectoral share of capital income $sp_{i,t}$, and, as shown in (13), $si_{i,t}$ is also adjusted such that sectors with higher-than-average capital rental rates (higher $pf_{i,k,t}$) would get larger shares of investable funds.⁸ Interested readers may refer to Dervis et al. for details.⁹

$$si_{i,t} = sp_{i,t} \left(1 + \mu \cdot \frac{pf_{i,k,t} - \overline{pf_{i,k,t}}}{\overline{pf_{i,k,t}}} \right) \quad (13)$$

⁷ The model treats government as a passive entity which simply collects taxes and receives transfers from abroad to finance its consumption, transfers to household or abroad, and savings.

⁸ The investible funds mobility parameter is set to $\mu = 0.5$ in this study.

⁹ See p. 175-178 in Dervis et al. (1982).

A3. Sensitivity Analysis with Different CO₂ Capture Rates

The sensitivity analysis with two hypothetical CO₂ capture rates (99% and 79%) and the same unit cost (40.36 US\$/ton-CO₂) as Ansolabehere *et al.* (2007) is provided. Taking the scenario of *Both with CCS* for instance, even with a capture rate of nearly 100%, an over 6% GDP loss is still observed, compared to a 9.5% GDP loss with the benchmark CO₂ capture rate (89%), as shown in **Figure 17**. With a higher CO₂ capture rate, although the total electricity supply in later years increases relative to the 89% capture rate case, as the carbon penalty on fossil-based generation is lowered, the decrease in electricity supply relative to the BAU level remains significant. With a lower CO₂ capture rate (79%), fossil-based generation will have to pay a higher carbon penalty especially in later years. As a result, the GDP and total electricity supply decrease further. In either case, a huge change in industrial structure is necessary. Therefore, the main findings of this study remain unchanged.

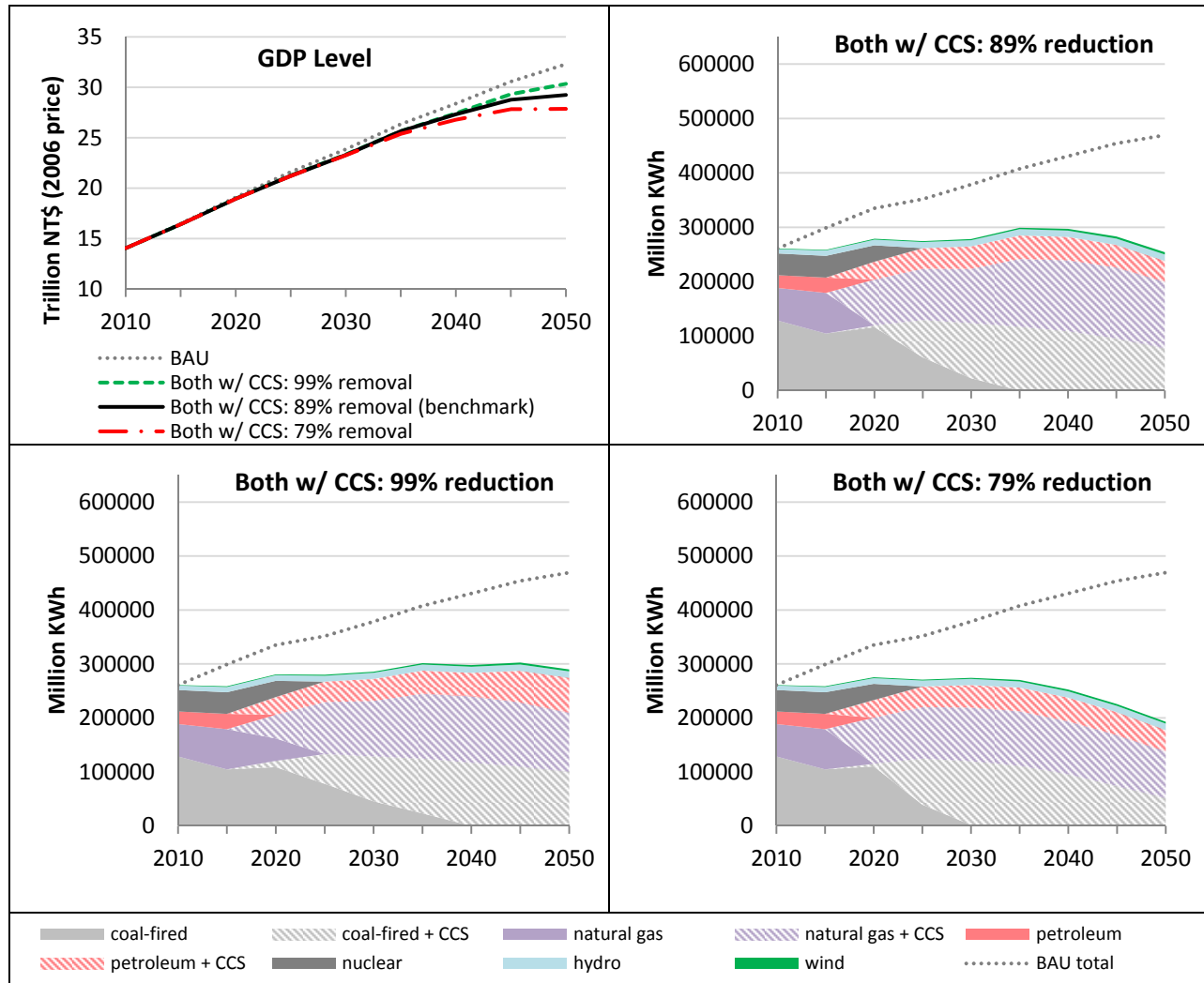


Figure 17. GDP levels and electricity output structures.

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